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# UTILITY PATENT APPLICATION TRANSMITTAL

(Only for new nonprovisional applications under 37 C.F.R. § 1.53(b))

| | |
|---|---|
| Attorney Docket No. | 82408 |
| First Inventor or Application Identifier | Carol A. Becker |
| Title | VISIBLE LIGHT pH CHANGE FOR ACTIVATING POLYMERS AND OTHER pH DEPENDENT REACTANTS |
| Express Mail Label No. | EL579517764US |

jc826 U.S. PTO 05/12/00

jc525 U.S. PTO 09/574987 05/12/00

**APPLICATION ELEMENTS**
See MPEP chapter 600 concerning utility patent application contents.

ADDRESS TO: **Assistant Commissioner for Patents Box Patent Application Washington, DC 20231**

1. [X] * Fee Transmittal Form (e.g., PTO/SB/17) (Submit an original and a duplicate for fee processing)
2. [X] Specification [Total Pages 21] (preferred arrangement set forth below)
   - Descriptive title of the Invention
   - Cross References to Related Applications
   - Statement Regarding Fed sponsored R & D
   - Reference to Microfiche Appendix
   - Background of the Invention
   - Brief Summary of the Invention
   - Brief Description of the Drawings (if filed)
   - Detailed Description
   - Claim(s)
   - Abstract of the Disclosure
3. [X] Drawing(s) (35 U.S.C. 113) [Total Sheets 5]
4. Oath or Declaration [Total Pages ]
   a. [ ] Newly executed (original or copy)
   b. [X] Copy from a prior application (37 C.F.R. § 1.63(d)) (for continuation/divisional with Box 16 completed)
      i. [ ] DELETION OF INVENTOR(S) Signed statement attached deleting inventor(s) named in the prior application, see 37 C.F.R. §§ 1.63(d)(2) and 1.33(b).

***NOTE FOR ITEMS 1 & 13: IN ORDER TO BE ENTITLED TO PAY SMALL ENTITY FEES, A SMALL ENTITY STATEMENT IS REQUIRED (37 C.F.R. § 1.27), EXCEPT IF ONE FILED IN A PRIOR APPLICATION IS RELIED UPON (37 C.F.R. § 1.28).***

5. [ ] Microfiche Computer Program (Appendix)
6. Nucleotide and/or Amino Acid Sequence Submission (if applicable, all necessary)
   a. [ ] Computer Readable Copy
   b. [ ] Paper Copy (identical to computer copy)
   c. [ ] Statement verifying identity of above copies

**ACCOMPANYING APPLICATION PARTS**

7. [X] Assignment Papers (cover sheet & document(s))
8. [ ] 37 C.F.R.§3.73(b) Statement (when there is an assignee) [ ] Power of Attorney
9. [ ] English Translation Document (if applicable)
10. [ ] Information Disclosure Statement (IDS)/PTO-1449 [ ] Copies of IDS Citations
11. [X] Preliminary Amendment
12. [X] Return Receipt Postcard (MPEP 503) (Should be specifically itemized)
13. [ ] * Small Entity Statement(s) (PTO/SB/09-12) [ ] Statement filed in prior application, Status still proper and desired
14. [ ] Certified Copy of Priority Document(s) (if foreign priority is claimed)
15. [X] Other: Copy of parent application, Serial No. 09/137,008

**16. If a CONTINUING APPLICATION,** check appropriate box, and supply the requisite information below and in a preliminary amendment:

[ ] Continuation [X] Divisional [ ] Continuation-in-part (CIP) of prior application No: 09 / 137,008

Prior application information: Examiner E. Wong Group / Art Unit: 1741

**For CONTINUATION or DIVISIONAL APPS only: The entire disclosure of the prior application, from which an oath or declaration is supplied under Box 4b, is considered a part of the disclosure of the accompanying continuation or divisional application and is hereby incorporated by reference. The incorporation can only be relied upon when a portion has been inadvertently omitted from the submitted application parts.**

**17. CORRESPONDENCE ADDRESS**

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| Signature | Peter A. Lipovsky | Date | 9 May 00 |

Navy Case No. 82408

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

In re application of:
CAROL A. BECKER

Examiner: XXXX
Art Unit: XXXX

This application is a division of:
Serial No. 09/137,008
Filed: 20 August 1998

FOR: VISIBLE LIGHT pH CHANGE FOR ACTIVATING POLYMERS AND OTHER pH DEPENDENT REACTANTS

**PRELIMINARY AMENDMENT**

Hon. Commissioner of Patents and Trademarks
Washington, DC 20231

Sir:

In conjunction with the filing of a divisional application under 37 CFR 1.53(b) of parent case Serial No. 09/137,008, filed 20 August 1998, the following amendment is submitted. For this divisional application, please amend the parent application as follows:

**In the Disclosure:**

On page 1, between lines 3 and 4, please insert the following:

--CROSS-REFERENCE TO RELATED APPLICATION

This application is a division of United States Patent Application Serial Number 09/137,008, filed 20 August 1998.--

On page 8, line 19, replace "conduction" with --conjunction--.

On page 9, line 18, replace "tetramethylethelendiamine" with --tetramethylethylenediamine--.

I hereby certify that this correspondence is being deposited with the U. S. Postal Service as first class mail in an envelope addressed to: Commissioner of Patents and Trademarks Washington, D. C. 20231 on 9 May 2000
Date

9 May 2000 Ruth Durisher
Date of signature Signature

On page 14, line 9, replace "$(H_2SO_{4)}$" with --$(H_2SO_4)$--.

On page 16, line 5, replace "$(H_2SO_{4)}$" with --$(H_2SO_4)$--.

**In the Claims:**

Please cancel claims 1-3; 15-22; and 25-26.

Please amend the remaining claims as follows:

CLAIM 6 (amended)

The apparatus of claim 5 in which said irradiation excites said anthracene [is excited] to emit phosphorescence.

Please add the following new claims:

CLAIM 27

The apparatus of claim 7 wherein said anthracene is in its protonated form.

CLAIM 28

The apparatus of claim 27 in which said polymer is a polyelectrolyte fiber.

CLAIM 29

The apparatus of claim 28 in which said polyelectrolyte fiber is polyacrylic acid-polyvinyl alcohol (PAA-PVA).

CLAIM 30

The apparatus of claim 29 in which said pH change in said solution is within plus or minus 1 pH value of a null point pH value of said polyelectrolyte fiber.

CLAIM 31

The apparatus of claim 7 in which said polymer is a polymer gel.

CLAIM 32

The apparatus of claim 31 in which said polymer gel is an acrylamide gel.

CLAIM 33

The apparatus of claim 32 in which said pH change in said solution is within plus or minus 1 pH value of a null point pH value of said polymer gel.

## Remarks

Applicant hereby respectfully requests that the above-identified parent application be amended as indicated. The present application is intended as a divisional application of Serial Number 08/137,008 for which a final Office Action has been received. Applicant does not wish for the cited parent application to go abandoned, and desires that the method claims of the parent application be issued as a U.S. Patent. In this divisional application, apparatus and further method claims are presented pertaining to the invention described in the description of parent application Serial Number 08/528,386.

**Navy Case No. 82408**

By this amendment, Applicant has amended the disclosure to be one and the same as the parent application as amended. The method claims of the original application have been canceled by this amendment with the exception of claims 23 and 24. The original apparatus claims, some of which are amended by this preliminary amendment, as well as additional new apparatus claims are hereby presented.

Any inquiry concerning this case should be directed to Applicant's attorney, Mr. Peter Lipovsky at (619) 553-3001.

Respectfully submitted,

by Peter A. Lipovsky

PETER A. LIPOVSKY
Registration No. 32,580
Attorney for Applicant

26 April 2000
Commanding Officer
Attention: Peter A. Lipovsky
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Navy Case 78990

# VISIBLE LIGHT pH CHANGE FOR ACTIVATING POLYMERS AND OTHER pH DEPENDENT REACTANTS

## BACKGROUND OF THE INVENTION

This invention relates generally to a method and apparatus for producing a pH change in a solution. More specifically, the invention relates to producing a pH change in a solution by irradiating the solution with visible light. With greater specificity, but without limitation thereto, the invention relates to using light to alter the pH of a solution to thereby cause an expansion and/or contraction of a pH dependent polymer immersed in the solution.

There exist a number of natural and synthetic fibers and gels that are expandable and contractible in volume when activated by an environmental change, such as exposure to a change in solvent composition, temperature, pH, electric field or photo irradiation, for example. As a commercially exploitable technology, the fibers and gels have applications in many fields, such as, for example, use in sensors, switches, motors, pumps, non-metallic operations and use in the medical and robotic fields where it is envisioned that these materials will be able to carry out the function of human muscle tissue.

The work of W. Kuhn and B. Hargitay as described in "Muskelahnliche Arbeitsleistung Kunstlicher Hochpolymerer Stoffe", Z. Elektrochemie **1951**, *55*(6), 490-502, incorporated by reference herein is one example of a synthesized polymer material capable of expansion and/or contraction. When the Kuhn and Hargitay polyacrylamide fiber, known as polyacrylic acid-polyvinyl alcohol (PAA-PVA), is placed within a solution of appropriately increasing pH, a 10% increase in fiber length is claimed to be observed.

Similarly, the work of T. Tanaka, D. Fillmore, S-T. Sun, I. Nishio, G. Swislow, and A.

Shah described in the article "Phase Transitions in Ionic Gels" Phys. Rev. Lett. **1980**, *45*(20), 1636-1639, incorporated by reference herein discloses an observed 400% volume collapse for a polyacrylamide gel disposed in a 50% acetone-water solvent mixture in which the pH of the solvent is lowered at constant temperature and solvent composition.

The work of Kuhn and Hargitay as well as Tanaka and Fillmore et al use a typical approach to changing the pH of a solution. In this approach, the pH is changed by manually dripping an acid or base into the solution. This technique, known as the "acid drip" method, relies upon the rate of the diffusion of hydrogen ions to a polymer site and is considered undesirably slow for certain polymer applications, such as use in synthetic muscles.

Besides the pH activation method of Kuhn and Hargitay and Tanaka and Fillmore et al, there exist electrical polymer activation schemes in which p-electron conjugated conducting polymers and electronically doped non-conducting polymers are electrically activated (expanded and contracted). An example of this activation method has been characterized by Shahinpoor et al as described in the article of D.J. Segalman, W.R. Witkowski, D.B. Adolf, and M. Shahinpoor titled: "Theory and Application of Electrically Controlled Polymeric Gels", Smart Materials and Structures, Vol. 1 (no. 1), M.V. Gandhi and B.S. Thompson (Eds.), London: Chapman and Hall, **1992**, 95-100. Like the pH activation method described above, the Shahinpoor et al method depends on the slow diffusion of ions to the active site of a polymer and therefore is also considered too slow for certain polymer applications such as use in synthetic muscles.

In addition to the activation approaches described above, there exist optical activation methods for causing volume changes in polymer fibers and gels. Noteworthy of these is the

work of M. Irie and D. Kunwatchakun described in "Photoresponsive Polymers. 8. Reversible Photostimulated Dilation of Polyacrylamide Gels Having Triphenylmethane Leuco Derivatives", Macromolecules **1986**, *19*(10), 2476-2480. The Irie-Kunwatchakun studies were among the earliest on photoinduced volume changes in polymer gels. Photosensitive molecules, such as leucocyanide and leucohydroxide, were incorporated directly into a polymer's network. Irradiation with UV light produced a 2.2-fold reversible dimension change, but no significant volume change (phase transition) took place in the polymer studied, as the UV light-induced pH change was far from the pH null point of the polymer gel. Thus the magnitude of the dimension change was not optimized for certain applications such as robotics.

In the work of researchers Mamada andTanaka as described in A. Mamada, T. Tanaka, D. Kungwatchakun, and M. Irie in "Photoinduced Phase Transition of Gels", Macromolecules **1990**, *23*, 1517-1519 and as described in A. Mamada, T. Tanaka, D. Kungwatchakun, and M. Irie in United States Patent Number 5,242,491 titled: "Photo-Induced Reversible, Discontinuous Volume Changes in Gels" and issued Sep 7, 1993, photoinduced phase transitions in gels were observed. The copolymer used was that of Irie-Kunwatchakun described above. At a given temperature, the polymer gel discontinuously swelled in response to UV irradiation and shrank when the UV light was removed. It is hypothesized that this swelling is due to dissociation into ion pairs, thereby increasing internal osmotic pressure within the gel. The shrinking process of this method is governed by ion diffusion and recombination, making the speed of the reverse process impossible to control, thereby hindering its usefulness in many polymer actuator applications.

In either of the UV studies described above, the UV radiation can cause undesired ionization, photolysis and molecular ligation of a utilized polymer.

Finally, in the work of A. Suzuki and T. Tanaka described in the article "Phase Transition in Polymer Gels Induced by Visible Light", Lett. Nature **1990**, *346*, 345-347, visible light was used to irradiate a gel containing a light-sensitive chromophore located in the backbone of an expandable and contractible copolymer. The chromophore absorbed the light and the light energy was then dissipated locally as heat by radiationless transitions, the result of which increased the "local" temperature of the polymer. Unlike the UV studies, the polymer expansion is a rapid process and is due to the direct heating of the polymer network by light. Yet the process of returning the polymer to its original size requires cooling, which becomes increasingly difficult as the temperature of the surrounding solution approaches the temperature of the polymer. This reverse process is too slow for many polymer uses such as in synthetic muscles.

Because many reactions are based on either acid or base catalyzations, including those of the polymers described above, researchers have investigated various approaches to promoting rapid pH changes. Such has been the case of Anthony Campillo et al as described in the article by A.J. Campillo, J.H. Clark, R.C. Hyer, S.L. Shapiro, K.R. Winn, and P.K. Woodbridge titled: "The Laser pH Jump", Proc. Intl. Conf. Lasers '78, Orlando, FL, Dec 11-15, **1978**, Chem. Phys. Lett. **1979**, *67*(2), 218-222; the article by A.J. Campillo, J.H. Clark, S.L. Shapiro, K.R. Winn, and P.K. Woodbridge, titled: "Excited-State Protonation Kinetics of Coumarin 102", Chem. Phys. Lett. **1979**, *67*(2), 218-222; the article by J.H. Clark, S.L. Shapiro, A.J. Campillo, K.R. Winn, titled: "Picosecond Studies of Excited-State Protonation and Deprotonation Kinetics. The

Laser pH Jump", J. Am. Chem. Soc. **1979**, *101*(3), 746-748; and United States Patent Number 4,287,035 issued to John H. Clark, Anthony J. Campillo, Stanley L. Shapiro, and Kenneth R. Winn on Sep. 1, 1981.

The work of Campillo et al relies on excited-state proton transfer reactions to change the $[H^+]$ of a solution by several orders of magnitude. Campillo et al used a picosecond spectroscopy tool to directly measure excited-state deprotonation-protonation reaction rate constants. To promote a pH change, a UV laser with a pulse width of 20 picoseconds was used to excite 2-naphthol-6-sulfonate to a higher ($S_1$) electronic state. From the measured rate constants, Campillo et al determined that the excited-state $pK_a$ value was 1.9, as opposed to the ground-state value of 9.1. This 7-unit change in $pK_a$ corresponds to a 7-order of magnitude increase in the acid dissociation constant, $K_a$. Campillo's findings are consistent with earlier studies which show that excited-state $K_a$ values can differ from ground-state values by many orders of magnitude, see the disclosure of J.F. Ireland and P.A.H. Wyatt titled:"Acid-Base Properties of Electronically Excited States of Organic Molecules", Adv. Phys. Org. Chem. **1976**, *12*, 131-221.

Campillo et al claim that a major use of their technique is initiation of acid-base catalyzed ground-state reactions. For example, the reactants A and B are present in solution at pH 7. The ground state reaction, A + B --> C, occurs only at pH 4. By exciting the Campillo et al "jump molecule", 2-naphthol-6-sulfonate, a subnanosecond jump from pH 7 to pH 4 can be achieved, thereby enabling the desired ground-state reaction. Referring to FIG. 1, a schematic state energy level diagram illustrates the path by which the "jump molecule" 2-naphthol-6-sulfonate travels to

produce the pH change described. The 2-naphthol-6-sulfonate is irradiated with UV light and is excited from ground state $S_0$ to first excited singlet state $S_1$. Radiative decay (florescence) then occurs bringing the molecule back to its ground state.

A major drawback of the Campillo technique is the extremely short duration of the accompanying pH change, typically 10 nanoseconds. While Campillo proposes that the excited state duration, and hence pH change, could be prolonged through use of repetitious irradiation, such an irradiation would require a bombardment of photons on the order of a million times a second. An additional shortcoming of the Campillo technique, when utilized with expandable and contractible polymers such as those described above, is that the utilized UV radiation promotes undesirable polymer ionization, photolysis and other molecular ligation. Additionally, the extremely narrow illumination path (0.1 mm or 5D-6 cubic centimeters) provided by the utilized 266 nanometer laser is considered insufficient to effectively illuminate an expandable/contractible polymer to undergo an appreciable change in volume.

## SUMMARY OF THE INVENTION

The invention provides a method and apparatus of rapidly changing the pH of a solution by way of a pH jump molecule that is activated by visible light. An application of the present invention is the ground-state reaction of changing the volume of an expandable and contractible polymer for simulated muscle applications as well as for other applications.

To permit these applications, it is desirable (1) to use a source of excitation energy that is not harmful to a utilized polymer; (2) to produce an *in-situ* pH change in which hydrogen ions become rapidly present at a polymer site; (3) to sustain the resultant pH change long enough and

in a volume large enough for desired ground-state reactions to occur, for example, the fully reversible expansion and contraction of a polymer; and (4) to provide a mechanism for efficient dissipation of heat produced as a result of the source of excitation energy.

Candidate pH "jump molecules" considered suitable for providing sufficient polymer actuation (activation) should possess the following characteristics:

(1) the jump molecules should have long lifetimes at room temperature, e.g 10 milliseconds;

(2) the jump molecule acidity constants should be grossly different in ground and triplet states, e. g., 7 orders of magnitude;

(3) the resultant pH change should go through the midpoint (pH null point) of the utilized polymer; and

(4) either the non-protonated or the protonated form of the jump molecule should absorb in the visible region of the spectrum.

In accordance with the present invention, an apparatus and method incorporating these desirable features are disclosed. The invention includes a pH jump molecule that permits visible light excitation to provide a long lasting pH change to a pH dependent polymer or other pH driven reactant. The attendant pH change occurs rapidly (in nanoseconds) and will last for the excited state lifetime of the jump molecule. Further irradiation by either a continuous wave or appropriately pulsed laser can sustain the pH change indefinitely. Heat resulting from the light activation is efficiently discharged by radiative decay through room temperature phosphorescence lifetimes existing on the order of milliseconds. Thus an expandable and

contractible polymer can be made to respond rapidly to a change in pH while the radiant heat-release mechanism of the invention allows the polymer to return to its initial configuration in a millisecond time frame, suitable for a variety of useful applications, including robotics.

Accordingly, it is an object of this invention to provide a method and apparatus for producing a rapid pH change in a solution.

A further object of this invention is to produce a rapid pH change in a solution that is useful in causing the expansion and/or contraction of a polymer.

Another object of this invention is to produce a rapid pH change in a solution that lasts long enough and is prevalent enough to be useful in causing the expansion and/or contraction of a polymer.

Still another object of this invention is to produce a rapid pH change in a solution that is useful in causing the expansion and/or contraction of a polymer while minimizing damage to the polymer.

Still yet another object of this invention is to produce a rapid pH change in a solution by irradiating the solution with visible light.

Yet another object of this invention is to produce a pH change in a solution by irradiating the solution with visible light in which any heat produced by the light is rapidly dissipated.

Other objects, advantages and new features of the invention will become apparent from the following detailed description of the invention when considered in conduction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic state energy level diagram.

FIG. 2 is illustrates the pH expansion and contraction dependence of an exemplary polymer, in this case an acrylamide gel.

FIG. 3 describes ΔpK values for various families of molecules

FIG. 4 illustrates the light absorbance of anthracene versus wavelength.

FIG. 5 illustrates the pH expansion and contraction dependence of another exemplary polymer, in this case a polyacrylic acid- polyvinylalcohol (PAA-PVA) fiber.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

In the expandable and contractible polymer world, a term of art has evolved that describes the large and easily perceptible change in volume that occurs when such a polymer, whether it be a gel or a fiber, is exposed to a particular change in the pH of a solution in which the polymer is immersed. This term of art is known as a "phase transition", and describes the physical phenomenon that takes place when the polymer is exposed to a narrow change in pH that passes through what is know as the pH null point of the polymer.

Referring to FIG. 2, there is shown a graphical depiction of such a phase transition. This illustration, taken from the 1980 Physical Review Letter of T. Tanaka and D. Fillmore et al referred to above, shows the response of a polymer network of an acrylamide gel that has been hydrologized in a 4% (volume) N,N,N, N-tetramethylethelenediamine (TEMED) solution. The quantity $\varphi/\varphi^*$ represents the swelling ratio which is the ratio of the final polymer network concentration to the initial polymer network concentration. The smooth curve is for gels immersed in water. The discontinuous curve is for gels in a 50% acetone-water mixture. In

either case, as pH is increased, the gel swells; as the pH is decreased, the gel shrinks.

For the acetone-water mixture shown in FIG. 2, the sharp s-shaped curve is characteristic of a phase transition. This behavior is referred to as a phase transition because an enormous amount of polymer swelling-shrinking occurs within a very narrow range of pH values. Capitalizing on this phenomenon, the greatest leverage for polymer activation can be achieved by finding a polymer-polymer activation system that has a $pK_a$ at the midpoint of the pH curve (or what is otherwise referred to as the null point of the polymer). The closer that the ground state $pK_a$ of a candidate "jump molecule" is to the null point of a polymer, the greater will be the variability of polymer volume for a given quantity of excitation energy. By using such a jump molecule, a small change in pH to either side of the midpoint will expand or contract the polymer by the largest amount possible, optimizing polymer dimensional change for use in robotics or other applications.

The term pK is a shorthand indicating the strength of an acid ($pK_a$) and is defined as the $-\log_{10} K$ in which K is the characteristic equilibrium constant K, represented by:

$$K = [H^+][B]/[BH^+]$$

where $[H^+]$ is the hydrogen ion concentration and [B] is the concentration of the conjugate base. When the amount of one of these constituents is varied, the others will adjust to keep K constant.

During the course of scientific research, the inventor constructed kinetic equations for the 3-level system of FIG. 1. Referring again to FIG. 1, an ideal "jump molecule" will be excited from ground state energy level ($S_0$) to first excited singlet state energy level ($S_1$), and return to

the ground state via triplet state energy level ($T_1$). The radiationless transition and radiative decay via phosphorescence will function as a "sink" for the molecules and because of their combined long lifetime, a prolonged molecule excited state will exist. The pH change produced by this excitation will last for the life of this excited state.

Repeated runs with many different candidate jump molecules predicted the requirements necessary to sustain a desired pH change:

(1) jump molecules should have long excited state lifetimes at room temperature, e.g., 10 milliseconds;

(2) jump molecule acidity constants must be grossly different in the triplet and ground states, e.g., 7 orders of magnitude;

(3) the resultant pH change should go through the midpoint (pH null point) of a utilized polymer; and

(4) either the non-protonated or the protonated form of the jump molecule should absorb in the visible region of the spectrum.

A great many molecules with functional groups were eliminated based upon being disqualified by the above requirements.

For example, the phenones are considered undesirable because the lifetimes of the protonated and non-protonated forms are very different, providing a rapid excited state deactivation channel. An example of this is benzophenone, having an unprotonated lifetime of 100 milliseconds and a protonated lifetime of 62 nanoseconds.

In addition, a great many functional groups were eliminated based upon small $\Delta pK$

values, $\Delta pK$ in this instance being the difference between first triplet state pK value minus the ground state pK value ( $pK(T_1) - pK(S_0)$ ), as can be seen in FIG. 3.

In Table 1, characteristics of the carbon acids are described. The carbon acids shown exhibited long excited-state lifetimes $\tau_p$ (p for phosphorescence) , large $\Delta pK$ values, and have $\Delta pK$ values that pass through a desired polymer null point, however the excitation wavelength $\lambda_{00}$ necessary to initiate a pH change falls within the ultraviolet. In this table, "obs" means "observed" and "c" means "calculated".

**TABLE 1**

| | $\tau_p$ (msec) | $pK(S_0)$ | $pK(S_1)$ | $pK(T_1)$ | $\lambda_{00}$ (nm) |
|---|---|---|---|---|---|
| **fluorene** | **0.35** | **23.04** | **-5.96(c)** | **7.54(c)** | **300** |
| **9-phenylflourene** | **obs** | **18.6** | **-10.7(c)** | **4.2(c)** | **305** |
| **9-cyanflourene** | **obs** | **11.4** | **-12.4(c)** | **5.0(c)** | **300** |

Through the process of elimination, several families of molecules satisfied the pH jump molecule requirements stated above. One of these are the polynuclear aromatic hydrocarbons (PAC's) which are bases.

Of these, the PAC, anthracene, fits well with certain well established polymers. Referring to FIG. 4, the protonated form of this molecule is confirmed. In FIG. 4, an absorbance versus wavelength profile shows the zero-time spectrum for protonated anthracene. The peak at 424 nm is the only peak within the visible region of the spectrum which decreases with time, and is the signature of anthracene's protonated form. It is this peak that is used to activate the

anthracene polymeric actuator with visible light.

Referring to FIG. 5, the contractile-expansion characteristics of the Kuhn-Hargitay polyacrylic-acid - polyvinylalcohol (PAA - PVA) polymer are shown. The Kuhn-Hargitay polymer fiber undergoes a phase transition between pH levels of 5 and 5.5, having a pH null point of approximately 5.3, as shown by the "Lange des Fadens" or "Length of Fiber" solid line.

Referring now to Table 2, specifications for utilizing protonated anthracene in coordination with the polymer described by Kuhn-Hargitay referred to above are shown.

**TABLE 2**

pH change and species concentrations
BH+ only absorbing, pH =5.0, 413.1 nm

BH+ <--> B + H+

Anthracene Jump Molecule

| | Ground | Singlet | Triplet | Lamda = 413.1 nm<br>Log(eps) | epsilon |
|---|---|---|---|---|---|
| pK's | 3.8 | 13.6 | 10.3 | | |
| Lifetimes nS (mS) | | 10.0 | (10.0) | | |
| B | 9.7D-4 | 1.5D-21 | 3.0D-11 | 0.04 | 1 |
| BH+ | 6.4D-4 | 2.0D-11 | 2.0D-4 | 4.38 | 23988 |

| Initial Concentrations: | | Final pH: | | | |
|---|---|---|---|---|---|
| pH | 5.0 | 5.48 | | | |
| [H+] | 1.0D-5 | 3.3D-6 | | | |
| [B] | 9.8D-4 | | | | |
| [BH+] | 2.0D-4 | Watts | 4.2 | Photons/sec | 9.3D+18 |
| Total B | 1.0D-3 | V cm3 | 1.0 | P/cm3-sec | 9.3D+18 |

413.1 nm = Center Kr+ line: 406.7, 413.1, 415.4

By utilizing visible light, the protonated form $BH^+$ of anthracene is disassociated into its base (B)

and hydrogen ion ($H^+$) constituents to prompt a pH change from 5 to 5.48. As can be seen, the $\Delta pK$ ( $pK(T_1)$ - $pK(S_0)$ ) of anthracene is 10.3 - 3.8, permitting such a large scale pH change. The calculation in Table 2 is based on a $pK(S_0)$ value for anthracene found in Mackor.. E.L., Hofstra, A., and Van Der Waals, J. H., 1958, in an article entitled "The Basicity of Aromatic Hydrocarbons", Trans. Faraday Soc., vol. 54, 66.

For use with the referenced Kuhn-Hargitay polymer, the desired protonated form of anthracene is derived by dissolving enough anthracene in cyclohexane, as described in Table 2, so that the resulting concentration of non-protonated anthracene is 9.8D-4 moles/liter when the pH is adjusted to 5.0 by the addition of sulfuric acid ($H_2SO_4$). The mixture is then vigorously shaken in a separatory funnel, causing the anthracene to diffuse from the cyclohexane to the sulfuric acid to form a solution of protonated anthracene.

For the polymer-anthracene combination described, a BeamLok 2080 krypton ion laser was used to irradiate the polymer system at 413.1 nanometers and 4.2 watts. The one cubic centimeter irradiation volume is large enough to house a polymer of macroscopic dimensions as the jump molecule provides a pH change from 5.0 to 5.48. Because of the 10 millisecond prolonged excited state of the anthracene jump molecules, the continuous wave laser will permit constant pH elevation until the irradiation is cut-off, at which time the excited-state jump molecules will decay to the ground state and reassociate, causing a return to the original pH in a few milliseconds. Importantly, the heat created by the molecules absorbing the irradiated light is released as light of a longer wavelength. Full polymer reversibility, which is not hindered by the slow dissipation of heat, is therefore made possible for use in many polymer applications,

including robotics.

Besides use of a continuous wave irradiation source, a pulsed laser having a repetition rate of 100 times a second at 42 millijoules will also suffice. This repetition rate will prompt a pulse every 10 milliseconds, permitting continuous pH elevation.

Referring now to Table 3, specifications for utilizing protonated anthracene in coordination with the polymer described by Tanaka-Fillmore et al referred to above are shown. The protonated form $BH^+$ of anthracene coordinates well with the Tanaka polymer in which the null point of this polymer (3.8 pH) corresponds with the ground state pKa value of the anthracene.

## TABLE 3

pH change and species concentrations
BH+ only absorbing, pH =3.7, 413.1 nm

BH+ <--> B + H+

Anthracene Jump Molecule

| | Ground | Singlet | Triplet | Lamda = 413.1 nm Log(eps) | epsilon |
|---|---|---|---|---|---|
| pK's | 3.8 | 13.6 | 10.3 | | |
| Lifetimes nS (mS) | | 10.0 | (10.0) | | |
| B | 6.4D-4 | 3.2D-21 | 6.9D-11 | 0.04 | 1 |
| BH+ | 1.8D-4 | 2.3D-11 | 1.8D-4 | 4.38 | 23988 |

| Initial Concentrations: | | Final pH: | | | |
|---|---|---|---|---|---|
| pH | 3.7 | 3.9 | | | |
| [H+] | 2.0D-4 | 1.3D-4 | | | |
| [B] | 7.1D-4 | | | | |
| [BH+] | 2.9D-4 | Watts | 6.3 | Photons/sec | 1.4D+19 |
| Total B | 1.0D-3 | V cm3 | 1.0 | P/cm3-sec | 1.4D+19 |

```
413.1 nm = Center Kr+ line:  406.7, 413.1, 415.4
```

For use with the Tanaka-Fillmore polymer, the desired protonated form of anthracene is derived by dissolving enough anthracene in cyclohexane, as described in Table 3, so that the resulting concentration of non-protonated anthracene is 7.1D-4 moles/liter when the pH is adjusted to 3.7 by the addition of sulfuric acid ($H_2SO_4$). The mixture is then vigorously shaken in a separatory funnel, causing the anthracene to diffuse from the cyclohexane to the sulfuric acid to form a solution of protonated anthracene.

For the polymer-anthracene combination described, a BeamLok 2080 krypton ion laser may be used to irradiate the polymer system at 413.1 nanometers and 6.3 watts. The one cubic centimeter irradiation volume is large enough to house a polymer of macroscopic dimensions as the jump molecule provides a pH change from 3.7 to 3.9. The 10 millisecond prolonged excited state, permits the continuous wave laser to maintain a constant elevated pH level. Once the irradiation is cut-off, the excited-state jump molecules will decay to the ground state and reassociate, causing a return to the original pH in a few milliseconds. As before stated, the heat created by the jump molecules absorbing light will be efficiently discharged as light of a longer wavelength.

Obviously, many modifications and variations of the invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as has been described.

THE CLAIMS

What is claimed is:

1. A method comprising:

forming a solution containing anthracene; and

irradiating said solution with visible light of a wavelength and of an intensity to establish a pH change in said solution.

2. The method of claim 1 in which said anthracene is in its protonated form.

3. A method according to claim 2 in which said anthracene is excited to emit phosphorescence.

4. An apparatus comprising:

a solution containing anthracene; and

a source of visible light

in which said source of visible light is used to irradiate said solution at a wavelength and of an intensity to establish a pH change in said solution.

5. The apparatus of claim 4 in which said anthracene is in its protonated form.

6. The apparatus of claim 5 in which said anthracene is excited to emit phosphorescence.

7. An apparatus comprising:

a solution containing anthracene;

a polymer disposed in said solution, said polymer having the characteristic of changing its volume in response to a change in pH; and

a source of visible light for irradiating said solution with light of a wavelength and of an intensity to establish a pH change in said solution so that when said solution is irradiated with said visible light said polymer undergoes a change in volume.

8. The apparatus of claim 7 in which said polymer is a polyelectrolyte fiber.

9. The apparatus of claim 8 in which said polyelectrolyte fiber is polyacrylic acid-polyvinyl alcohol (PAA-PVA).

10. The apparatus of claim 9 in which said pH change in said solution is within plus or minus 1 pH value of a null point pH value of said polyelectrolyte fiber.

11. The apparatus of claim 7 in which said polymer is a polymer gel.

12. The apparatus of claim 11 in which said polymer gel is an acrylamide gel.

13. The apparatus of claim 12 in which said pH change in said solution is within plus or minus

1 pH value of a null point pH value of said polymer gel.

14. The apparatus of claim 7 in which said anthracene is in its protonated form.

15. A method comprising:

forming a solution containing anthracene;

disposing a polymer in said solution, said polymer having the characteristic of changing its volume in response to a change in pH; and

irradiating said solution with a source of visible light of a wavelength and of an intensity to establish a pH change in said solution so that said polymer undergoes a change in volume in response to said pH change.

16. The method of claim 15 in which said polymer is a polyelectrolyte fiber.

17. The method of claim 16 in which said polyelectrolyte fiber is polyacrylic acid-polyvinyl alcohol (PAA-PVA).

18. The method of claim 17 in which said pH change in said solution is within plus or minus 1 pH value of a null point pH value of said polyelectrolyte fiber.

19. The method of claim 15 in which said polymer is a polymer gel.

20. The method of claim 19 in which said polymer gel is an acrylamide gel.

21. The method of claim 20 in which said pH change in said solution is within plus or minus 1 pH value of a null point pH value of said polymer gel.

22. The method of claim 15 in which said anthracene is in its protonated form.

23. A method comprising:

forming a solution of a compound that exhibits a change in pH upon irradiation with visible light; and

changing said pH in said solution by irraditing said compound with said visible light so that said compound is elevated from a ground state energy level to a higher singlet state energy level to a triplet state energy level.

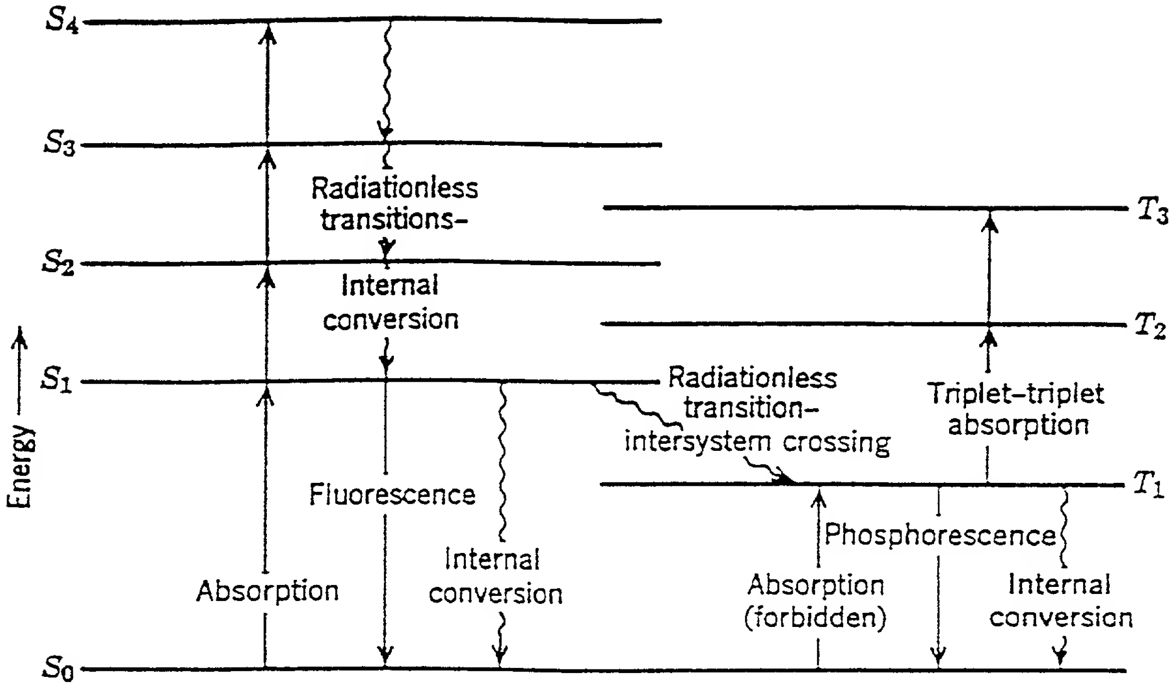
24. A method according to claim 23 in which said pH change exists for at least one millisecond.

25. A method according to claim 24 In which said compound is anthracene.

26. A method according to claim 25 in which said anthracene is in its protonated form.

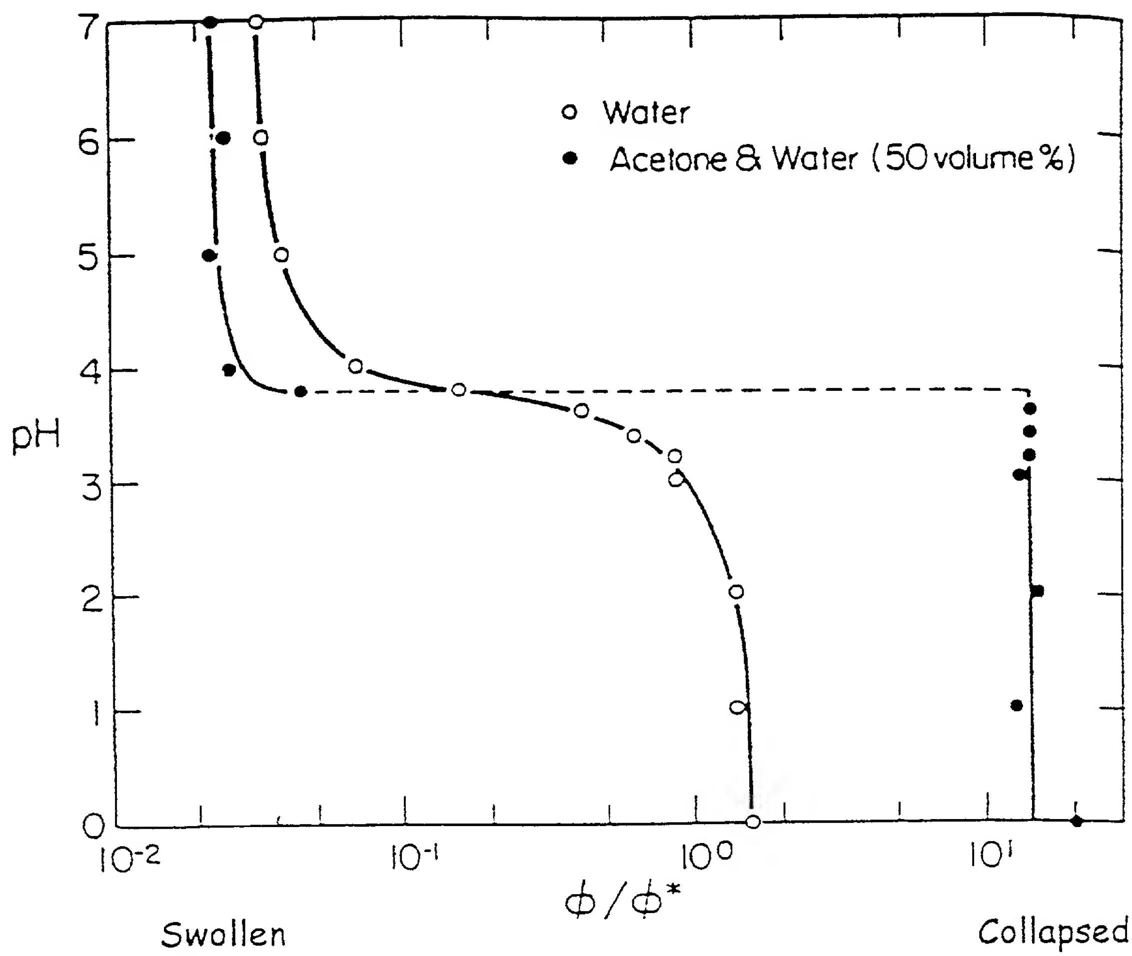
# ABSTRACT OF THE DISCLOSURE

A method and apparatus for initiating a rapid and long-lasting pH change to a pH dependent polymer or other pH driven reactant is provided by a pH jump molecule in solution. Visible light is used to excite the pH jump molecule. The attendant pH change occurs rapidly (in nanoseconds) and can be maintained by continuous wave light or by an appropriately pulsed light. Heat resulting from the light activation is efficiently discharged by radiative decay through room temperature phosphorescence lifetimes existing on the order of milliseconds.



$S_4$
$S_3$
$S_2$
$S_1$
$S_0$
$T_3$
$T_2$
$T_1$
Energy
Radiationless transitions-
Internal conversion
Radiationless transition-
intersystem crossing
Triplet-triplet absorption
Fluorescence
Internal conversion
Absorption
Phosphorescence
Absorption (forbidden)
Internal conversion

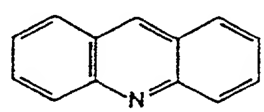

FIG. 1



Water
Acetone & Water (50 volume %)
pH
7
6
5
4
3
2
1
0
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$\phi/\phi^*$
Swollen
Collapsed


FIG. 2

| Reaction | Example | $pK(S_0)$ | $pK(S_1)$ | $pK(T_1)$ | $\lvert\Delta pK\rvert$ |
|---|---|---|---|---|---|
| $-CO_2H$ <--> $-CO_2^- + H^+$ | 2-Naphthoic acid | 4.2 | 11.0 | 4.0 | 0.2 |
| $-OH$ <--> $-O^- + H^+$ | 2-Naphthol | 9.5 | 2.8 | 8.1 | 1.4 |
| $-NH_3^+$ <--> $-NH_2 + H^+$ | 2-Naphthylamine | 4.1 | -2.0 | 3.3 | 0.8 |
| $-NO_2H$ <--> $-NO_2^- + H^+$ | Nitrobenzene | -11.3 | 2.3 | -9.3 | 2.0 |
| Ar $NH^+$ <--> Ar N $+ H^+$ | Acridine | 5.5 | 10.6 | 5.6 | 0.1 |




$\Delta pK = pK(T_1) - pK(S_0)$

FIG. 3

# Anthracene Zero-time Spectrum

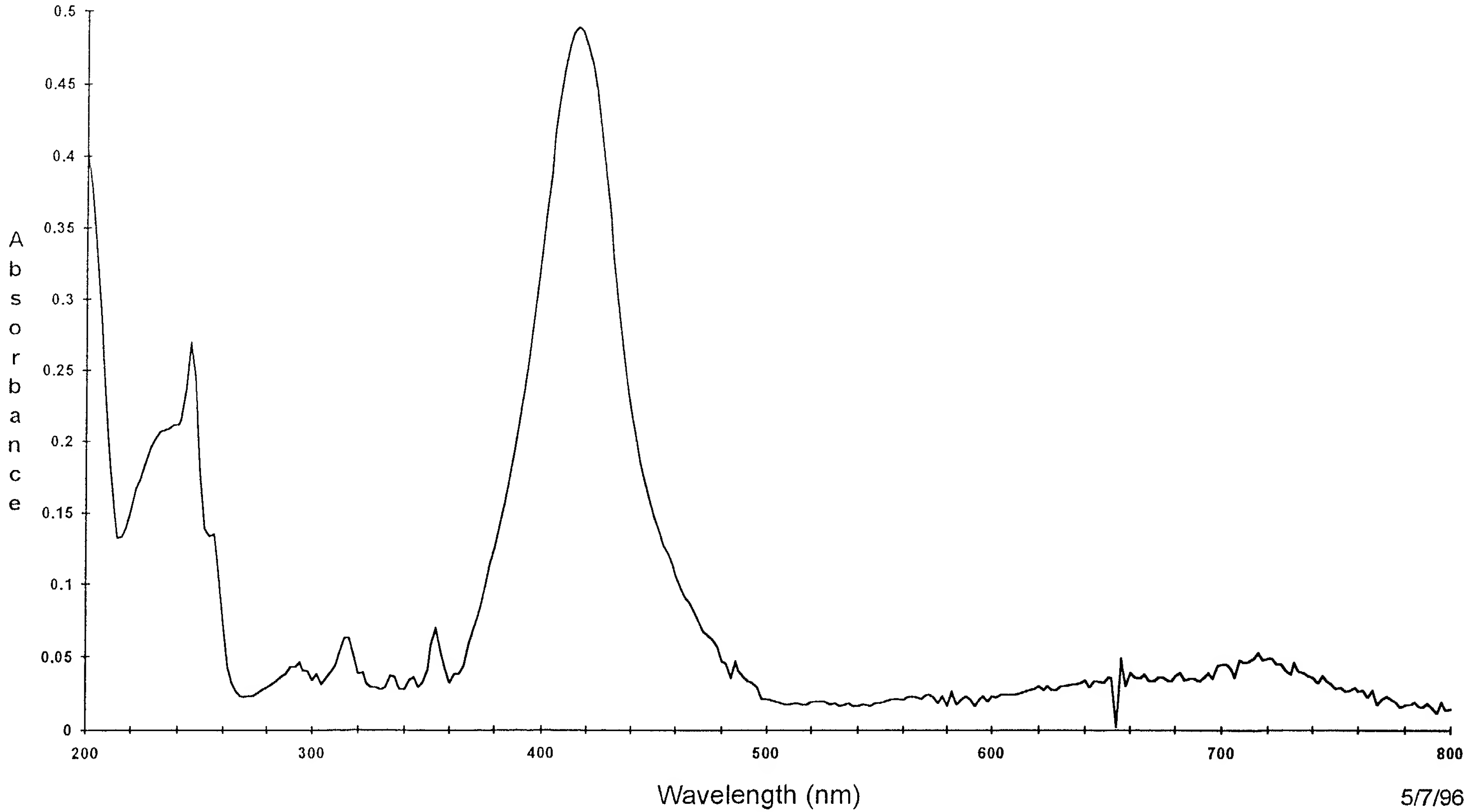



FIG 4

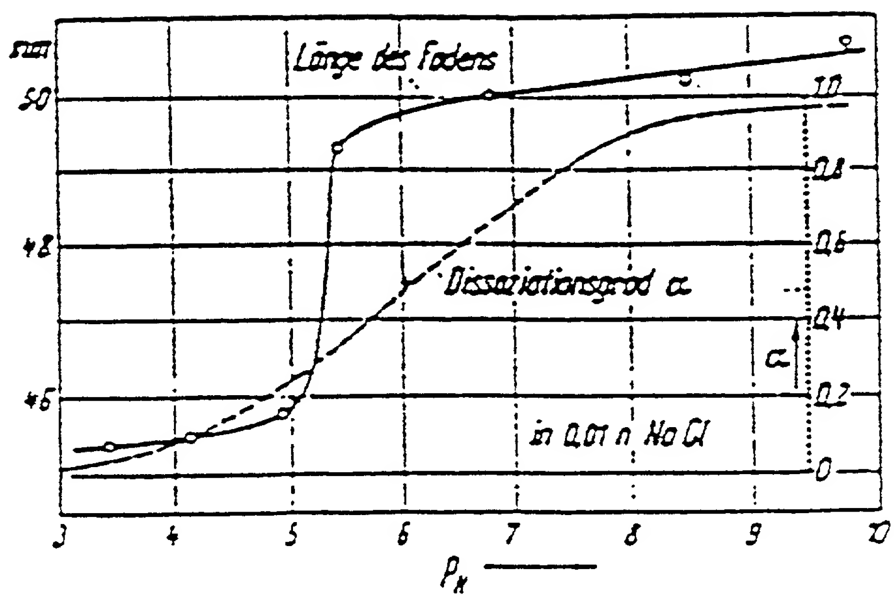

mm
50
48
46
Länge des Fadens
Dissoziationsgrad α
in 0,01 n NaCl
1,0
0,8
0,6
0,4
0,2
0
α
3
4
5
6
7
8
9
10
pH

FIG. 5

Please type a plus sign (+) inside this box → [X]

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# DECLARATION FOR UTILITY OR DESIGN PATENT APPLICATION (37 CFR 1.63)

[X] Declaration Submitted with Initial Filing OR [ ] Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16 (e)) required)

| | |
|---|---|
| Attorney Docket Number | 78990 |
| First Named Inventor | Carol A. Becker |
| ***COMPLETE IF KNOWN*** | |
| Application Number | -- / |
| Filing Date | -- |
| Group Art Unit | -- |
| Examiner Name | -- |

**As a below named inventor, I hereby declare that:**

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

VISIBLE LIGHT pH CHANGE FOR ACTIVATING POLYMERS AND OTHER pH DEPENDENT REACTANTS

*(Title of the Invention)*

the specification of which

[X] is attached hereto

OR

[ ] was filed on (MM/DD/YYYY) [ ] as United States Application Number or PCT International Application Number [ ] and was amended on (MM/DD/YYYY) [ ] (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56.

I hereby claim foreign priority benefits under 35 U.S.C. 119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or of any PCT international application having a filing date before that of the application on which priority is claimed.

| Prior Foreign Application Number(s) | Country | Foreign Filing Date (MM/DD/YYYY) | Priority Not Claimed | Certified Copy Attached? YES | NO |
|---|---|---|---|---|---|
| | | | [ ] | [ ] | [ ] |
| | | | [ ] | [ ] | [ ] |
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| | | | [ ] | [ ] | [ ] |

[ ] Additional foreign application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto.

I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below.

| Application Number(s) | Filing Date (MM/DD/YYYY) | |
|---|---|---|
| | | [ ] Additional provisional application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto. |



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# DECLARATION — Utility or Design Patent Application

I hereby claim the benefit under 35 U.S.C. 120 of any United States application(s), or 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application.

| U.S. Parent Application or PCT Parent Number | Parent Filing Date (MM/DD/YYYY) | Parent Patent Number *(if applicable)* |
|---|---|---|
| | | |

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As a named inventor, I hereby appoint the following registered practitioner(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith: ☐ Customer Number [ ] → *Place Customer Number Bar Code Label here*
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| Name | Registration Number | Name | Registration Number |
|---|---|---|---|
| Harvey Fendelman | 27,030 | | |
| Michael A. Kagan | 33,188 | | |
| Peter A. Lipovsky | 32,580 | | |
| Eric James Whitesell | 38,657 | | |

☐ Additional registered practitioner(s) named on supplemental Registered Practitioner Information sheet PTO/SB/02C attached hereto.

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

**Name of Sole or First Inventor:** ☐ A petition has been filed for this unsigned inventor

| Given Name (first and middle [if any]) | Family Name or Surname |
|---|---|
| Carol A. | Becker |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Inventor's Signature | Carol A. Becker | | | | | Date | 8/19/98 |
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| City | Solana Beach | State | CA | ZIP | 92075-1215 | Country | U.S.A. |

☐ Additional inventors are being named on the ____ supplemental Additional Inventor(s) sheet(s) PTO/SB/02A attached hereto